Space and Earth Terminal Sizing for Future Mars Missions

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NASA is investigating potential communications architectures to support future missions to Mars, with a time horizon out to about 2040. We examined a wide range of Earth-surface, Earth-orbiting, Mars-orbiting, and Mars-landed assets with both radio frequency and optical capabilities, and estimated the size, weight, power, and comparative cost of spacecraft telecommunications subsystems along with their comparative costs. Link attributes needed to achieve a fixed set of desired data rate capabilities were derived, assuming a planned set of Earth stations. For the trunk link from Mars to Earth, the required return data rates considered were 50, 75, 125, and 250 Mbps, and the required forward data rates considered were 30 and 50 Mbps. For proximity links, the required forward and return data rates (symmetric) ranged from 0.36 Mbps to 100 Mbps. The communication channels considered were UHF (75 cm wavelength) for proximity links only, and X-band (3.6 cm wavelength), Ka-band (0.81 cm wavelength), and optical (808, 976, 1064, and 1550 nm wavelength) for both proximity and trunk links. Optical solutions provided substantial size and spectrum constraint advantages, but mixed advantages and disadvantages on mass and power. System cost was lower if the RF capability of space assets was increased to permit the number of arrayed RF Earth stations to be limited to two.

I. Nomenclature

AU	=	Astronomical Unit
bps	=	bits per second
nm	=	nanometer
RF	=	Radio Frequency
UHF	=	Ultra High Frequency
W	=	Watt

II. Introduction

The NASA Space Communication and Navigation (SCaN) program is investigating potential communications architectures to support future missions to Mars, with a time horizon out to about 2040. Therefore we explored various options for communications assets with capacity sufficient to meet the needs of these future missions, considering a wide range of Earth-, Earth-orbiting, Mars-orbiting, and Mars-landed assets. We also explored both radio frequency and optical capabilities, with the intent of identifying their relative strengths and weaknesses in the particular application of communication with Mars. In the process, we estimated the size, weight, power, and comparative cost of spacecraft telecommunications subsystems, and the comparative costs of Earth-based assets.

We assumed communication demand consistent with the forecasted needs of all deep space missions near Mars to be supported by the SCaN communications assets from now toward 2040, covering about 25 years into the

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future. Although there are significant uncertainties about human space flight missions to Mars, especially the degree of reliance on optical communications, we applied the working assumptions presently in use within NASA. These include a forecasted need for the first dedicated relay orbiter at Mars around 2031, a human spaceflight mission aligned with a 24-day Mars short-stay surface scenario, a crewed Mission to Phobos, and a collection of Mars orbiters and landers that will rely on a mix of radio frequency and optical communication. We also assumed SCaN's planned RF ground asset capacity for 2016-2040, the possibility of an Earth-based optical subnet with global coverage, and the possibility of an Earth orbiter carrying a substantial optical telescope for communication purposes.

III. Structure of the Study

The objective of our study was to find appropriate sizing for Mars telecommunications payloads to satisfy relevant scenarios developed by other studies: an RF ground asset capacity study covering calendar years 2016-2040, an RF ground asset capacity study covering 2016-2040, a Mars Mission Trend study for the Post-2025 period, a Mars Surface Scenario study for the Post-2030 period, and a Mars Interspace Scenario study for Post-2030. Broadly, those studies identified the need for one or more relay terminals in a Mars Areostationary orbit (altitude 17,000 km), serving a collection of Mars surface assets, and orbiters at various altitudes between the Areostationary relay and the Martian atmosphere. The general schema of communication is depicted in Figure 1.

The architectural tenets for the study consisted of the following:

1. Meet data rate goals for the trunk link
2. Minimize user spacecraft burden
3. Observe constraints set by spectrum and expected components available
4. Minimize total system cost

Using these tenets, we derived trunk and proximity link attributes that would be needed to achieve the desired communications capabilities, given an initial condition of a fixed set of data rate capabilities. For the trunk link from Mars to Earth, the required return data rates considered were 50, 75, 125, and 250 Mbps, and the required forward data rates considered were 30 and 50 Mbps. We considered possible communication channels consistent with spectrum regulations, at X-band (3.6 cm wavelength), Ka-band (0.81 cm wavelength), and also optical (808, 976,

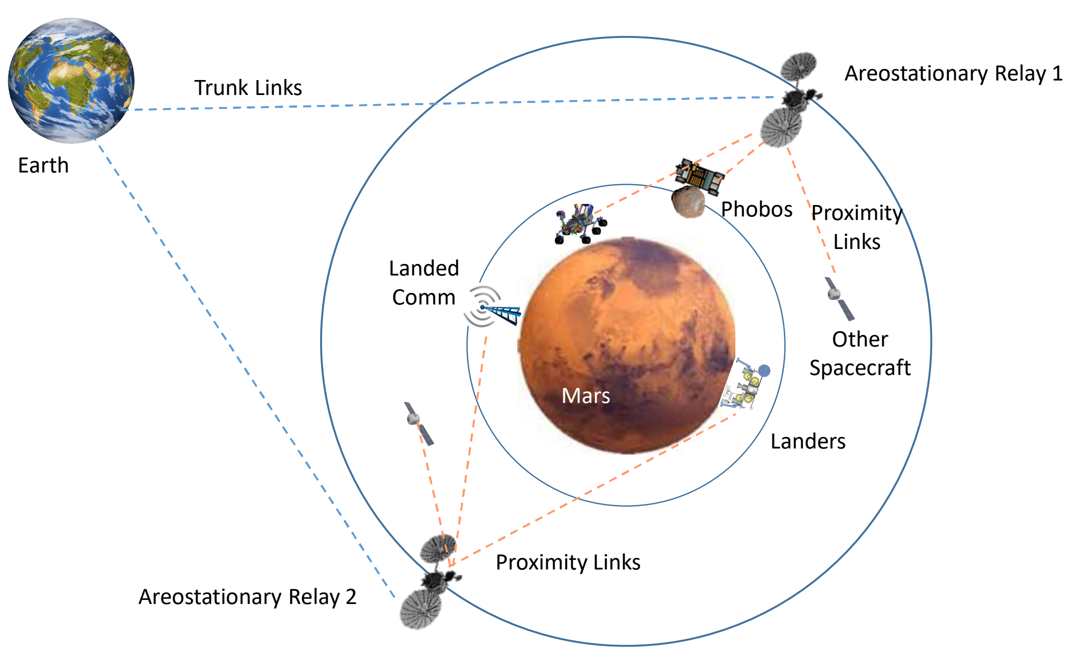

Figure 1. Schema of communication between Earth and Mars.

1064, and 1550 nm wavelength) which is free from spectral regulation. Given other constraints on the space terminals, these data rates tend to exclude X-band as a feasible communication channel due to spectrum regulations that limit the available bandwidth. However, we did derive link attributes for X-band forward and return capabilities that could be provided within the constraints of a radio system that is otherwise sized for Ka-band use at the full data rate. Such a capability could be used for a reliable backup channel for spacecraft command and telemetry, or for the highest priority science data. For proximity links, the required forward and return data rates (symmetric) ranged from 0.36 Mbps to 100 Mbps.

For communications assets on the Earth, we considered Deep Space Network stations of the 34-meter beam waveguide type, applied singly or as arrays of from two to six antennas. These stations were assumed to provide both X- and Ka-band forward and return services using high-power transmitters characteristic of the current development program underway in the Deep Space Network. We also considered four types of optical ground stations, providing return services at 1550 nm and an uplink beacon function, but not providing a forward service at the required data rates simply because we are not at this time aware of system solutions in that direction that would be practical in the immediate future, though it may become practical in the longer-term future. These were single 11.8-meter apertures, single and hybrid 8-meter RF-Optical apertures, and arrays of 4-meter optical apertures.

For orbiting communications assets at Mars, we considered Areostationary relays positioned at a distance of about 18,000 km from landed assets or orbiting terminals between Mars and an Areostationary orbiter. This is somewhat greater than the slant range to the Martian limb for surface assets (17,367 km) to allow for low-Mars orbiters up to 5,800 km. Other altitudes, such as Phobos at 9,376 km would still be possible at full rate over most of the portion of the orbit visible from the Areostat, and at reduced data rate in other portions. The Areostationary relays we considered had radio frequency antennas for trunk link communication of diameters of two to six meters in diameter, Ka-band transmitters in the range of 235 to 940 watts, and X-band transmitters of 50 watts. The relays also were considered to have optical telescopes of 20 to 50 cm diameter for trunk link communication, and optical transmitters of 15 to 50 watts. For proximity links at Mars, we considered UHF (75 cm wavelength), X-band, Ka-band, and optical terminals on the Areostationary orbiter. These had apertures of 6 meters, 3 meters, 30 to 75 cm, and 5 to 10 cm respectively in those bands.

For landed communications assets at Mars, we considered both radio and optical terminals. The radio terminals were considered to use UHF, X-band, or Ka-band. The UHF range was considered for compatibility with legacy assets operating on familiar operating concepts with broad-beam antennas. For UHF, following tenet two, we assumed a low-gain antenna with a 30-cm diameter helix, along with a 10 W transmitter, similar to existing landed assets. This is suitable for a lander that may be limited in pointing control for the antenna. For X-band, a low-gain antenna could not close the link at the required data rate, so again following tenet two, we assumed a 32 cm dish antenna requiring moderately accurate pointing, and a 10 W transmitter. This is suitable for a base station or a lander capable of moderately accurate pointing. For Ka-band, and for identical reasons, we assumed a 30 cm dish antenna requiring highly accurate pointing, and transmitter powers ranging from 200 milliwatt to 58 watt.

For communications assets in Earth orbit, we considered a 1.05-meter optical telescope, equipped with cryogenically cooled detectors equivalent in performance to what is presently available for terrestrial applications.

In addition to determining link attributes, we estimated the size, weight, and power (SWAP) of the space terminals, and their costs based on JPL historical records, and published scaling laws for astronomical observatories. We present only normalized, comparative costs in this paper, to permit discussion of tradeoffs between system components as a guide to finding preferable architectures. The normalized costs should not be used enable specific budgetary planning or commitments.

IV. Requirements

The study was conducted in two passes, the first pass driven by a need to compare the feasibility of multiple possible solutions for the various link types. The requirements were based on needs expressed by various stakeholders with minor consideration of feasibility of meeting those requirements. In the second pass, the feasibility was considered, and some requirements were reduced in order to keep the terminal characteristics, especially the Earth terminal characteristics, within a reasonable range of affordability. The requirements for the two passes are summarized in Table 1.

Table 1. Requirements for Mars-related Communications Links

Topic	First-pass requirement	Second-pass requirement
Trunk Link Topology	All RF option: X-band forward, X- and Ka-band return Combined RF/optical option: X-band forward, X- and Ka-band return, optical return	Ka-band forward Combined RF/optical return: X-band, Ka-band, optical
Trunk Link Data Rate	50 Mbps forward 250 Mbps return X-band unconstrained	30 Mbps forward 50, 75, 125 Mbps return
Proximity Link Topology	All RF option: UHF forward, UHF return, X-band forward, X-band return Combined UHF/optical option: UHF Forward, UHF Return, optical return Combined UHF/X/optical option: UHF forward, UHF return, X-band forward, X-band return, optical forward, optical return	Ka-band bi-directional (forward and return) Optical bi-directional (forward and return)
Proximity Link Data Rate	50 Mbps forward 50 Mbps return UHF unconstrained	0.5, 10, 50, 100 Mbps bi-directional (forward and return)
Optical Earth Terminal Type	12-meter monolithic 8-meter monolithic 8-meter optical/RF hybrid 4-meter optical array	8-meter optical/RF hybrid
Radio Earth Terminal Type	Deep Space Network 34m Beam Waveguide Antenna	Same
Mars Relay Location	Areostationary	Same
Mars Surface Element Location	Equatorial spot region, latitude and longitude constrained to maintain elevation >45 deg to Areostationary relay	Same

V. Specific Communication Conditions – Trunk Links

For the trunk links, we chose to place bulk data transport on Ka-band or optical due to their potentially higher data rate capabilities compared to X-band. As the data rate capabilities for Ka-band and optical are more variable with weather, it tends to be advantageous from a data volume standpoint to operate the links at data rates close to the limit available in good weather (90th percentile for Ka-band, 67th percentile for optical). If data completeness is required when the link is operated this way, Automatic Repeat Query (ARQ) should be used to fill in gaps. This does not rule out adaptive data rates or modulations to maintain communications through adverse weather, but within available forecasting technology, the long round-trip light times associated with deep space missions tends to make adaptation slower than for near-earth mission. The result is that less data can be recouped this way for deep space than for near Earth. Nor does operating the link this way in the main rule out operating the link occasionally at lower data rates consistent with closing the link in worse weather in order to obtain high continuity with low latency, should operational needs dictate.

Some trunk data needs reliable data transport with lower latency (e.g. telemetry and command for the relay); we chose to route such data on X-band. Although the data rate capacity is lower, and limited by spectrum, we did not set a specific requirement on X-band data rate. Rather, we left the X-band rate unconstrained and derived the best feasible rate using antennas sized for Ka-band, along with transmitters that were sized to provide spectrum-limited capacity without increased spacecraft burden.

Frequencies and wavelengths for the trunk links were: for X-band, 7145 MHz forward, 8430 MHz return; for Ka-band 37.25 GHz forward, 34.3 GHz return; and for optical 1550 nm return only. The orbital situation was for Mars at a Sun-Earth-Probe (SEP) angle of 10 degrees, near to Mars maximum range from Earth, 2.5 AU for the first pass and 2.675 AU for the second pass. We assumed an Earth terminal elevation of 45 degrees for the first pass, and 20 degrees for the second pass. Radio frequency modulation was BPSK for Ka-band, and GMSK for X-band to observe spectrum requirements. Radio coding was Turbo (1784, 1/2) except for the Ka-band uplink, where we considered both Turbo (1784, 1/2) and Low-density Parity Check (LDPC) codes (1024, 1/2) and (4096, 1/2) to reduce spacecraft processing requirements. For optical, we assumed Pulse Position Modulation (PPM) with variable order and rate, optimized, and serial-concatenated (SC-PPM) coding.

We assumed that the RF Ground Terminals would be DSN 34-meter Beam Waveguide (BWG) antennas, arrayed if needed to meet data rates. In the first pass, arrays of up to four 34-meter antennas were allowed. In the second pass, data rate requirements were adjusted downward to require no more than two antennas arrayed. Transmitters were assumed to have powers of 20 kW for X-band and 1 kW for Ka-band. The DSN does not presently have 1 kW Ka-band transmitters, only 300 W, but research is under way to develop higher power transmitters.

In the first pass, we considered optical ground terminals with apertures of 12m, 2x 8 m array, 2 x 8m RF/optical hybrid array, and a 9x 4m array. In the second pass, the requirements were reduced to allow them to be satisfied with a single 8m RF/optical hybrid aperture. The downlink wavelength was assumed that of the current Deep Space Optical Terminal, or 1550 nm. In the course of the study we found a limit for downlink laser power around 15-17 W, too low to achieve the desired data rates with a single downlink laser. Therefore, we assumed three downlink lasers of 15 W slightly separated in wavelength, with data multiplexed between them to achieve the desired rate.

From the assumptions above, we derived the sizing of the Areostationary orbiter's radio and optical systems. In order to achieve 250 Mbps in the first pass, initially a 6 m body fixed dish antenna is needed for Ka-band, driven by two 250 W Traveling Wave Tube Amplifiers (TWTA) for a net power of 470W. The antenna, though large, is the smallest that could satisfy tenets one and two, within the allowable number of ground stations (four) associated with tenet 4. Such antennas are available on the market, and fit within several potential launchers. The transmit power is also large, but within known transmitter designs, and would not be a driver on spacecraft bus power for a mission with solar electric propulsion, though it might be for a spacecraft with less power. During the course of our study we found in the second pass that it is beneficial in advancing tenet four if the Ka-band transmitter power is increased to 940 W, because of a favorable cost trade between increasing the spacecraft capability to allow fewer Earth stations to be arrayed.

A number of existing transponders are capable of providing the necessary reception and transmission functions, among which we adopted the Universal Space Transponder (UST) just for concreteness in calculating mass and power.

For X-band, the same 6 m antenna is used, driven by a 50 W TWTA to provide 3 Mbps return data rate. Somewhat more data rate could be provide with more power, up to a spectral limit dictated by tenet 3.

For the optical system, we constrained the relay aperture to be no larger than 50 cm to keep the cost reasonable, considering the power law exponent of around 1.7 found by Stahl et al. for optical tube assemblies. With that aperture, 45 watts of transmitter power was needed to meet the required data rates, which we arranged as three 15 W transmitters multiplexed, constrained by an expectation of no more than 15-17 W from a single laser of the required speed.

We examined the possibility of receiving the optical trunk link near the Earth using a space-based, 1.05 m aperture. Using the relay trunk link characteristics otherwise derived from the combined data rate requirements and assumed use of a large Earth surface aperture, the space-based aperture is capable of receiving 10 Mbps.

VI. Specific Communication Conditions – Proximity Links

We placed all high-rate data transport for the proximity links on the frequencies other than UHF, and provided for UHF capability as a reliable but lower rate alternative for user terminals for which fine pointing needed for the higher frequencies was undesirable. The UHF data rate was unconstrained, so we designed for the best achievable with low-directivity antennas on the proximity asset, subject only to the constraint that the antenna on the relay could be no larger than that used for the Ka-Band trunk link. The frequency for UHF was 401 MHz, for X-band was 7145 MHz forward and 8430 MHz return, and for Ka-band was 26 GHz. Lacking any existing convention for Ka-band forward and return services, 26 GHz should be considered a median value that will eventually be separated into two frequencies distinguishing forward and return. For optical proximity links, the forward wavelength was 808 nm, and the return wavelength was 976 nm. The communication geometry was 45 degrees elevation on the Mars surface, communication distance 18,000 km between a Mars surface asset and an Areostationary relay. The sun-Earth-probe angle was assumed to be 10 degrees. Regarding weather, at RF there is no significant weather effect due to the thin atmosphere at Mars. For optical, statistics available are limited, but we adopted 3 dB atmospheric loss corresponding to the 70th

percentile value estimated by Edwards et al.[1] to maximize data volume. An additional 2 dB of loss would be needed for 90th percentile. We required 3 dB of margin in the link calculations. RF modulation was assumed to be BPSK, coded using Turbo (1784, ½), while optical Modulation was PPM with variable order and rate, optimized, and using SC-PPM coding.

From the assumptions above, we derived the sizing of both the proximity user terminals, and corresponding terminals on the Areostationary orbiter. The 50 Mbps data rates required in the first pass led to an X-band proximity link transceiver on the Areostationary relay having a 6 m antenna and 100W transmitter, while the surface asset needed a 33 cm dish antenna and a 100 W transmitter. For UHF in the first pass, we allowed up to a 6 m antenna and a 12 W transmitter, which achieved 360 kbps to and from a surface asset having a 30 cm helix antenna and a 10 W transmitter. This is a very large antenna, highly directive and requiring fine pointing. The large antenna on the relay could of course be downsized if a lower UHF data rate would suffice. In the service of tenet one, we dropped consideration of UHF in the second pass through the study. The 50 Mbps data rate led to an optical system on the relay with a 10 cm aperture and a 2 W, 808 nm transmitter. The resulting surface optical system was a 5 cm aperture and a 2 W 976 nm transmitter.

During the second pass, we focused on Ka-band and optical proximity links to reduce burden on both the relay and the surface asset. We found that a Ka-band link supported by a 75 cm dish antenna on the relay and a 30 cm dish on the surface asset could achieve bi-directional data rates of 0.5, 10, 50, and 100 Mbps if the relay had transmitter powers of 300 mW, 5.8 W, 29 W, and 58 W, and if the surface asset had transmitter powers of 120 mW, 2.4 W, 12.2 W, and 24 W. We note that these powers are lower than estimated by Edwards et al.[1], which we believe is due to different assumptions about optical receiver capability; we assumed near-ideal receivers capable of operating at the channel capacity.

VII. Estimated Size and Cost of Space Terminals

We estimated the size and cost of the derived RF space terminals described above, using a collection of radio equipment properties developed by the JPL Communications, Tracking, and Radar Division. The terminal properties, shown in Table 2, were based on flight equipment available on a commercial- or government-off-the-shelf basis, or previously used on NASA missions. The costs presented are normalized to arbitrary units to allow intercomparison between options while not tying the cost to specific flight hardware components or to specific base financial years. These costs are shown for architectural comparison purposes only and are not suitable for estimating an actual system cost for budgetary purposes.

We also estimated the size and cost of the derived optical space terminals described, summarized in Table 3. Lacking a historical database for space optical systems, we scaled from the 22 cm, 4 W Deep Space Optical Terminal described by Hemmati et al.[2] and Biswas et al.[3] We scaled volume of the optical telescope assembly (OTA) and the electronics as the cube of the diameter. Mass we scaled proportional to diameter to the 1.7 power for the OTA, proportional to power for the lasers, constant for the detectors, and proportional to diameter to the 1.5 power for actuators. Power for lasers was scaled proportional to power separately for lasers of 4 W and below, and for greater than 4 W. The former group was based on the Deep Space Optical Terminal; the latter group was based on an assumption of lasers having an efficiency of 10% with respect to input power. Power for optical components, electronics, and actuators was assumed independent of diameter. Costs for optical terminals (again with normalized units) were scaled using each of three theories:

Theory 1: Stahl et al[4] 2004 D^1.7 OTA

Theory 2: 50% fixed + 50% Meinel and Meinel[5] 2004 D^2.7 Observatory

Theory 3: 20% fixed + 80% Meinel and Meinel[5] 2004 D^2.7 Observatory

None of these theories is perfectly applicable, having been derived with experience from larger optical systems, and Earth-based. However they cover a range that includes similar scaling models previously used for deep space optical terminals[3], reflect the general trend of the cost, and include a range of possible power laws consistent with some of the known factors such as structural cost, optics manufacturing costs, engineering costs, and the like. In theories 2 and 3 we included a reasonable range of possible fixed costs associated with spacecraft systems engineering and testing, project management, and the like consistent with some other systems, though we do not claim to have precise information on that factor. The resulting range of costs between theories should be taken as a rough range, likely to need refinement when designs that are more detailed are developed.

Table 2. Estimated Size and Cost for RF Space Terminals
(see text for discussion of cost units)

Terminal	Volume l	Mass kg	Power W	Normalized Cost Units Nth Unit	Normalized Cost Units 1st Unit
X/X/Ka Areostat Trunk 50/75 Mbps	57,012	66.4	1011	116.6	198.0
X/X/Ka Areostat Trunk 125 Mbps	57,015	71.8	1891	124.8	225.1
Ka Prox Areostat 100 Mbps	105	7.7	94	29.3	46.7
Ka Prox Areostat 50 Mbps	105	6.1	49	23.9	33.1
Ka Prox Areostat 10 Mbps	102	2.8	9.5	5.4	11.9
Ka Prox Areostat 0.5 Mbps	101	2.5	2.5	3.8	9.3
Ka Prox Surface 100 Mbps	31	6.9	94	26.8	41.9
Ka Prox Surface 50 Mbps	31	5.3	49	21.3	28.3
Ka Prox Surface 10 Mbps	28	2	9.5	2.9	7.2
Ka Prox Surface 0.5 Mbps	27	1.7	2.5	1.3	4.5

Note: Volume of antenna for Ka Areostat is calculated from diameter 6m and height 2m, an estimate of the final antenna volume on orbit. The volume may be smaller at other times during the mission if the antenna were to be folded for launch.

Table 3. Estimated Size and Cost for Optical Space Terminals
(see text for discussion of cost units)

	Prox Surface				Prox Areostationary					Trunk					
Transmit	1.2 mW	25 mW	0.2W	0.5 W	1.2 mW	25 mW	0.2W	0.5 W	2W	4W	16W	23W	3x15W		
Aperture	5	5	5	5	10	10	10	10	10	22	50	50	50	cm	
Volume															
OTA	0.4	0.4	0.4	0.4	3.1	3.1	3.1	3.1	3.1	33	393	393	393	L	
Electronics	0.7	0.7	0.7	0.7	5.9	5.9	5.9	5.9	5.9	62	62	62	62		
Total	1.1	1.1	1.1	1.1	9.0	9.0	9.0	9.0	9.0	96	456	456	456		
Mass															
Optical	1.2	1.2	1.2	1.2	3.9	3.9	3.9	3.9	3.9	14.9	60	60	60.1	kg	
Laser	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.7	8.9	8.9	8.9		
Detectors	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8		
Actuator	2.3	2.3	2.3	2.3	6.5	6.5	6.5	6.5	6.5	21.2	72.7	72.7	72.7		
Total	4.3	4.3	4.3	4.4	11.2	11.2	11.2	11.3	11.6	37.7	142.6	142.6	142.6		
Power															
Laser	0.0	0.1	0.7	1.8	0.0	0.1	0.7	1.8	7.1	14.2	160	230	450.0	W	
Optical	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0		
Electronics	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5		
Actuator	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		
Total	26.5	26.6	27.2	28.3	26.5	26.6	27.2	28.3	33.6	40.7	186.5	256.5	476.5		
Cost				20					24	38	94	94	94	cost	Theory 1
				10					15	38	129	129	129		Theory 2
				4					8	38	313	313	313		Theory 3

Cost Scaling Laws
Theory 1: Stahl et al[4] 2004 D^1.7 OTA
Theory 2: 50% fixed + 50% Meinel et al[5] 2004 D^2.7 Observatory
Theory 3: 20% fixed + 80% Meinel et al[5] 2004 D^2.7 Observatory

VIII. Observations

Optical, Ka-band, and X-band are all physically capable of closing the required links with feasible spacecraft terminals. However, for a purely radio system, the Areostationary terminals would be quite large (~57,000 L), dominated by a 6 m dish antenna. Although antennas of that size are feasible, the volume is significant and tends to give an advantage in volume to optical solutions.

The UHF data rate for proximity links can be adjusted from a rate achievable with familiar low gain orbiter UHF antennas (10 kbps) up to 360 kbps using very large antennas comparable to trunk link. Such large antennas would not be practical in a system designed for multiple simultaneous proximity links unless they were multi-beam phased arrays, and even then might be too large to be practical. This was a driver to consider X-band, Ka-band, and optical for proximity links.

X-band can close the proximity links at 50 Mbps and maintain a familiar ops concept for surface elements, that is, modest pointing required for an X-band dish antenna, but not a familiar ops concept for the Areostationary terminal. The reason is that the X-band proximity link antenna at the Areostat is 6 m in diameter and highly directive. It would require fine pointing, not staring at the planet with a broad beam waiting for hailing from the user terminal. Furthermore, if the X-band antenna was a simple dish antenna it could only serve one, or a few adjacent, surface elements at a time with one beam. Multiple access would again require multi-beam phased array.

Another issue with X-band for the proximity links is that the full X-band spectrum allocation would be needed to handle the required data rate for a single user. Thus, a data rate-sharing scheme is required if multiple users must be served simultaneously. Typical solutions would be Frequency Division Multiple Access, Time Division Multiple Access, or Code Division Multiple Access.

Optical solutions provide substantial size advantages compared to the radio solutions with the same data rate capacity, but mixed advantages/disadvantages on mass and power. Optical could solve spectrum issues, and with multiple heads could provide multiple access for many users in less volume than RF solutions using multi-beam phased array antennas.

In the first pass through the study, we found large costs associated with Earth terminals, both for radio and optical. The costs were significant enough that the system cost could be lowered substantially by increasing the size and cost of the spacecraft relay trunk link elements. This we did in the second pass. This departs somewhat from the historical tenet that the least costly system for deep space will have very small equipment. The quantitative differences in this case are that the number of Areostats contemplated is relatively small, smaller than the number of Earth stations contemplated, and the fact that Earth stations are relatively expensive compared to the marginal cost of increasing the Areostat capabilities.

Also in the first pass, it became apparent that 12 m optical stations are likely to be significantly more expensive than 8m RF/optical hybrid stations. We considered arrays of 4m optical telescopes as an alternative; however, we found that given well-researched scaling laws[4,5] for Earth telescopes and presently understood costs for a single 4 m optical telescope, there was a cost penalty compared to a single large aperture. Receiver costs, controls and software cost, and an unfavorable exponent in power law for the Optical Telescope Assembly based on diameter (D^1.73) are the deterrents. However, there were limitations to the level of detail we explored for the receiver/controls and software cost; these need further detail to confirm the assumed scaling. The result of this observation was that we focused on 8 m telescopes in the second pass, in particular the RF/optical hybrid because of its cost advantage compared to a monolithic optical telescope. In all of the optical analysis for Earth stations we took advantage of the opportunity to reduce surface quality based on wavelength and the need only to collect photons; imaging-quality optics are not needed in a communications application.

We noticed substantial effects of elevation assumptions in the RF Earth terminal analysis. Our goal was to determine space and ground terminal sizing to enable a desired link capability. That begged a question: what does "link capability" mean in the context of a system whose performance varies substantially with elevation and to a lesser degree between sites. The issue is illustrated in Figure 2, which depicts variations in achievable RF data rate as a function of time of day on a particular day within the studied mission window. A similar, perhaps more pronounced variation applies to achievable optical data rates. In the RF case, at Ka-band, the achievable rate varies by about a factor of five during the day, as the relay rises and sets through varying elevations at each station. A customer might have different requirements from time to time that would dictate planning for an "Always On" data rate below the lowest rate supportable, for a "20 Degree Elevation" data rate that matched their scheduled time window, a "Best Handover Rate" when switching between stations, or a "Best Single Rate" if the mission needs the simplicity of a single data rate to avoid data rate changes. From a network design perspective, it might make sense to simplify specifications to a "Network Average" value that is a good predictor of the long-term average data return. In all of these cases, there are times of the day, indeed most of the day, when there is excess capability. This excess capability, if left unused, has implications for system cost of about 2-3 dB. That is, the cost may be 2-3 dB higher, or the data return per unit cost 2-3 dB lower, than it could be if the excess capability were removed by either downsizing the system or constantly varying the data rate to use the excess capability. Either of those two resolutions to the issue would require some changes to mission operating concepts, which historically have emphasized predictable, deterministic, constant, and high-continuity coverage. The third possible resolution, accepting a system that costs 2-3 dB extra, may be difficult considering the magnitude of the costs involved.

A final observation concerns the solar obscuration issue. From time to time, the Sun intercepts the communication line-of-sight between the Earth and Mars, interrupting communication. Many robotic deep space missions have been programmed to ride through the outage, but there is some concern that a manned mission may require continuous communication to mitigate risk. This topic is discussed further in a companion article[6].

IX. Conclusion

A summary of all the derived link characteristics appears in Table 4. We observe that spacecraft power and volume for radio frequency solutions are very large, around 500 to 1000 watts of power and 60,000 liters of volume dominated by antenna size in order to achieve the required data rates while minimizing total cost, specifically, by limiting the number of Earth antennas arrayed. We also observe that spectrum constraints at Mars limit X-band solutions to about 10 MHz of bandwidth. These links probably cannot efficiently provide higher-order modulations and coding within other constraints of practicality, unlike Earth-based solutions. In our study, optical solutions provided substantial size and spectrum constraint advantages, but mixed advantages and disadvantages on mass and power.

For the ground system, arrays of optical telescopes, given well-known scaling laws and presently understood costs, may not offer a cost advantage compared to a single large aperture. We also found that link sensitivity analysis to assumptions about required operating conditions on the Earth, specifically elevation angle, weather, and selection of specification in terms of minimum/average/best handoff/peak data rates, strongly influenced the system cost through the corresponding changes in the number of antennas needed for arrays. We also discovered that better system costs result if upper limits are set for size and quantity of Earth stations, while allowing larger (but still practical) space assets.

Figure 2. Sensitivity of data rate to elevation assumptions.

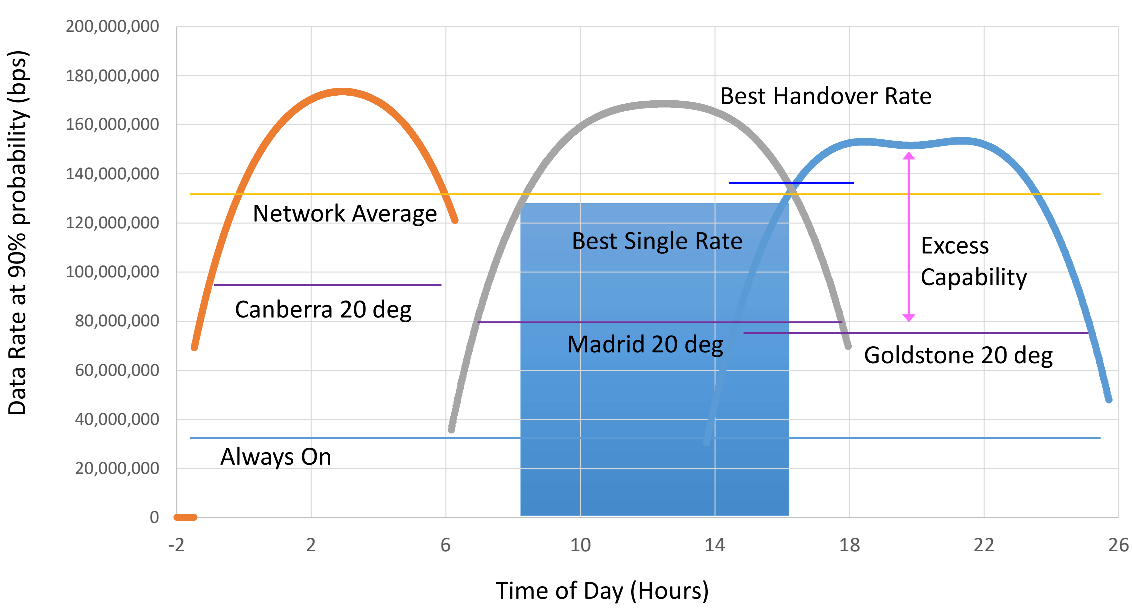

Table 4. Terminal and Link Attribute Summary

(a) Trunk Links

Link type	TT&C	Trunk	Trunk	Trunk	Trunk	Trunk	Trunk	Trunk	Trunk
Direction	Return	Return	Return	Return	Return	Return	Return	Return	Forward
Band	X	Ka	Ka	Ka	optical	optical	optical	optical	Ka
rate	1.55 Mbps	50 Mbps	75 Mbps	125 Mbps	50 Mbps	75 Mbps	125 Mbps	10 Mbps	30 Mbps
coding	Turbo (1784,1/2)	Turbo (1784,1/2)	Turbo (1784,1/2)	Turbo (1784,1/2)	SC-PPM	SC-PPM	SC-PPM	SC-PPM	LDPC (4096,1/2)
modulation	GMSK	BPSK	BPSK	BPSK	PPM	PPM	PPM	PPM	BPSK
link margin	3.2 dB	4.7 dB	2.9 dB	3.8 dB	3 dB	3 dB	3.6 dB	3 dB	2.9 dB
margin prob	0.977	0.977	0.977	0.977	-	-	-	-	0.999
weather prob	0.9	0.9	0.9	0.9	0.67	0.67	0.67	0.67	0.9
elevation	20 deg	20 deg	20 deg	20 deg	20 deg	20 deg	20 deg	vacuum	20 deg
Range km	4.01E+08	4.01E+08	4.01E+08	4.01E+08	4.01E+08	4.01E+08	4.01E+08	4.01E+08	4.01E+08
Range AU	2.675	2.675	2.675	2.675	2.675	2.675	2.675	2.675	2.675
SEP	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg
Freq	8.43 GHz	37.25 GHz	37.25 GHz	37.25 GHz	-	-	-	-	34.3 GHz
wavelength	3.6 cm	0.81 cm	0.81 cm	0.81 cm	1550 nm	1550 nm	1550 nm	1550 nm	0.87 cm
sender location	Mars	Mars	Mars	Mars	Mars	Mars	Mars	Mars	GDSCC
aperture	6m	6m	6m	6m	50 cm	50 cm	50 cm	50 cm	2x34 BWG
tx array gain	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	5 dB
Tx power	50 W	470 W	470 W	940 W	15.5 W	23 W	3x 15 W	3x 15 W	2x1 kW
volume	included>	57000 L	57000 L	57000 L	460 L	460 L	460 L	460 L	-
mass	included>	66 kg	66 kg	72 kg	140 kg	140 kg	140 kg	140 kg	-
power	included>	1000 W	1000 W	1900 W	190 W	260 W	480 W	480 W	-
receiver locatio	GDSCC	GDSCC	GDSCC	GDSCC	GDSCC	GDSCC	GDSCC	GEO	Mars
aperture	2x 34m BW	2x 34m BW	2x 34m BW	2x 34m BW	8 m	8 m	8 m	1.05 m	6 m
rcv array gain	2 dB	2 dB	2 dB	2 dB	0 dB	0 dB	0 dB	0 dB	0 dB
Noise	23 K	52 K	52 K	52 K	225kcps	225kcps	225kcps	225kcps	300 K
volume	-	-	-	-	-	-	-	-	^ included
mass	-	-	-	-	-	-	-	-	^ included
power	-	-	-	-	-	-	-	-	^ included

(b) Proximity Links

Link type	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity	Proximity
Direction	Return	Return	Return	Return	Forward	Forward	Forward	Forward	Return	Return	Return	Return	Forward	Forward	Forward	Forward
Band	Ka	Ka	Ka	Ka	Ka	Ka	Ka	Ka	optical	optical	optical	optical	optical	optical	optical	optical
rate	0.5 Mbps	10 Mbps	50 Mbps	100 Mbps	0.5 Mbps	10 Mbps	50 Mbps	100 Mbps	0.5 Mbps	10 Mbps	50 Mbps	100 Mbps	0.5 Mbps	10 Mbps	50 Mbps	100 Mbps
coding	Turbo (17	Turbo (17	Turbo (17	Turbo (17	Turbo (17	Turbo (17	Turbo (17	Turbo (17	SC-PPM	SC-PPM	SC-PPM	SC-PPM	SC-PPM	SC-PPM	SC-PPM	SC-PPM
modulation	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
link margin	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB	3 dB
margin prob	0.977	0.977	0.977	0.977	0.977	0.977	0.977	0.977	-	-	-	-	-	-	-	-
weather prob	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
elevation	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg	45 deg
Range km	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4	1.8e4
Range AU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SEP	-	-	-	-	-	-	-	-	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg
Freq	26 GHz	26 GHz	26 GHz	26 GHz	26 GHz	26 GHz	26 GHz	26 GHz								
wavelength									976 nm	976 nm	976 nm	976 nm	808 nm	808 nm	808 nm	808 nm
sender location	MSL	MSL	MSL	MSL	Areostat	Areostat	Areostat	Areostat	MSL	MSL	MSL	MSL	Areostat	Areostat	Areostat	Areostat
aperture	30 cm	30 cm	30 cm	30 cm	75 cm	75 cm	75 cm	75 cm	5 cm	5 cm	5 cm	5 cm	10 cm	10 cm	10 cm	10 cm
tx array gain	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB
Tx power	300 mW	5.8 W	29 W	58 W	120 mW	2.4 W	12.2 W	24 W	1.2 mW	25 mW	0.2W	0.5 W	35 mW	50 mW	0.25 W	0.6 W
volume	27 L	28 L	31 L	31 L	101 L	101 L	105 L	105 L	1.1 L	1.1 L	1.1 L	1.1 L	9 L	9 L	9 L	9 L
mass	1.7 kg	2.0 kg	5.3 kg	6.9 kg	2.5 kg	2.8 kg	6.1 kg	7.7 kg	4.3 kg	4.3 kg	4.3 kg	4.4 kg	11.2 kg	11.2 kg	11.2 kg	11.3 kg
power	2.5 W	9.5 W	49 W	94 W	2.5 W	9.5 W	49 W	94 W	26.5 W	26.6 W	27.2 W	28.3 W	26.5 W	26.6 W	27.2 W	28.3 W
receiver locatio	Areostat	Areostat	Areostat	Areostat	MSL	MSL	MSL	MSL	Areostat	Areostat	Areostat	Areostat	MSL	MSL	MSL	MSL
aperture	75 cm	75 cm	75 cm	75 cm	30 cm	30 cm	30 cm	30 cm	10 cm	10 cm	10 cm	10 cm	5 cm	5 cm	5 cm	5 cm
rcv array gain	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB
Noise	670K	670K	670K	670K	670K	670K	670K	670K	4e7 ph/s	4e7 ph/s	4e7 ph/s	4e7 ph/s	4e7 ph/s	4e7 ph/s	4e7 ph/s	4e7 ph/s
volume	101 L	102 L	105 L	105 L	27 L	28 L	31 L	31 L	9 L	9 L	9 L	9 L	1.1 L	1.1 L	1.1 L	1.1 L
mass	2.5 kg	2.8 kg	6.1 kg	7.7 kg	1.7 kg	2 kg	5.3 kg	6.9 kg	11.2 kg	11.2 kg	11.2 kg	11.3 kg	4.3 kg	4.3 kg	4.3 kg	4.4 kg
power	2.5 W	9.5 W	49 W	94 W	2.5 W	9.5 W	49 W	94 W	26.5 W	26.6 W	27.2 W	28.3 W	26.5 W	26.6 W	27.2 W	28.3 W

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